Phase Coherent Charge Transport in Graphene Billiards

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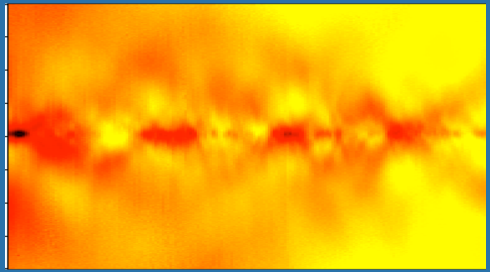
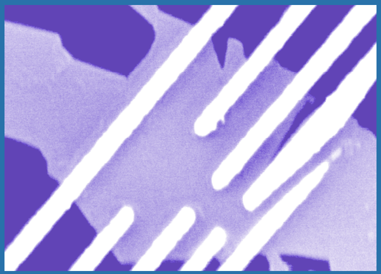
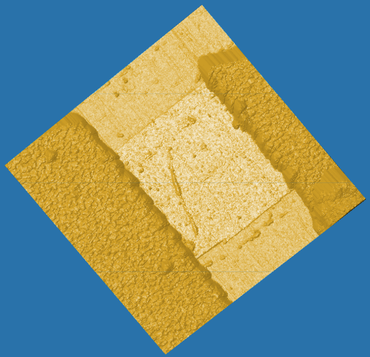






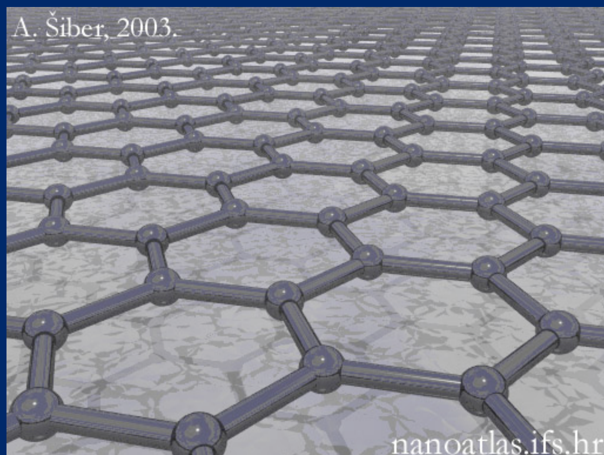
Outline

- Motivation
- Device fabrication
- Data and discussion

Normal electrodes	Minimum conductivity in graphene Ballistic, phase coherent transport
Superconduting electrodes	Superconducting Proximity effect Novel plasmon-mediated superconductivity (?)

- Conclusion and future work

Motivation



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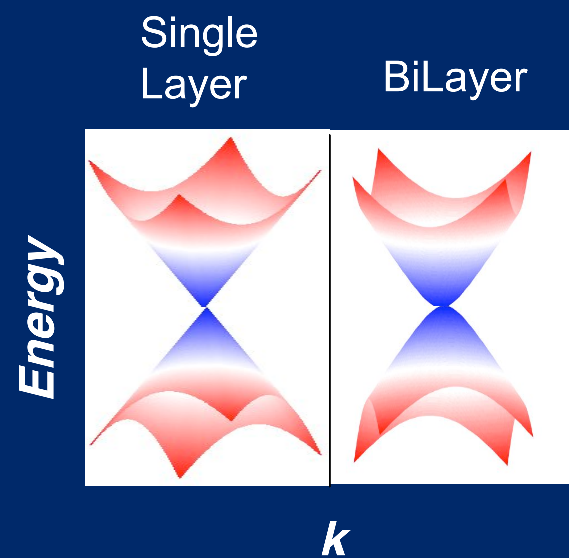
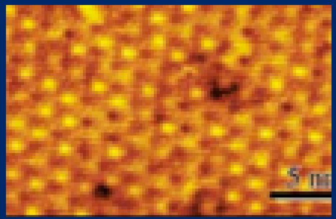


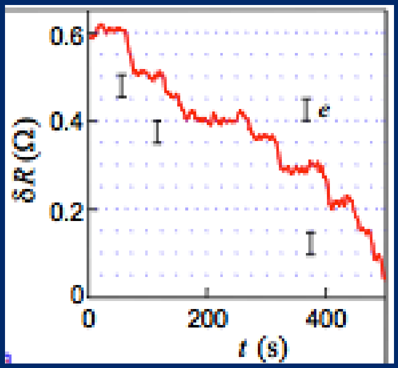
- Degeneracy of 2 sub-lattices
- Unique Dispersion Relations
- Massless Dirac Fermions --> Relativistic physics

Potential Applications

- With advantages of carbon nanotubes
  - ✓high thermal conductivity,
  - ✓high current density
  - ✓high mobility
- potentially compatible with lithographic techniques
- Chemical and biological sensors based on graphene
- Electronics, Spintronics, and Valley-tronics

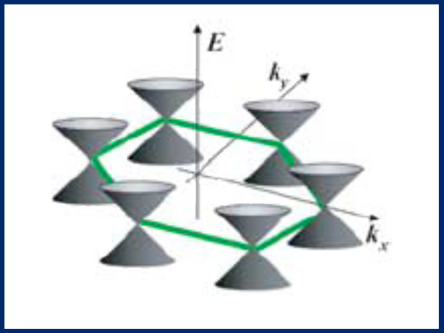


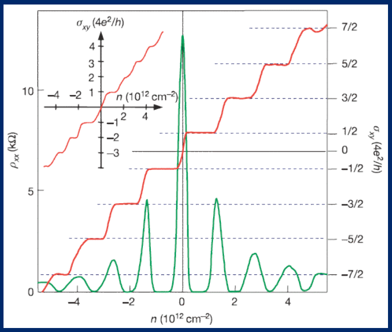
Epitaxially grown graphene
Berger *et al*, *Science* (2006)



Ultra-sensitive gas sensors
Schedin *et al*, preprint (2006).

Pioneering Work



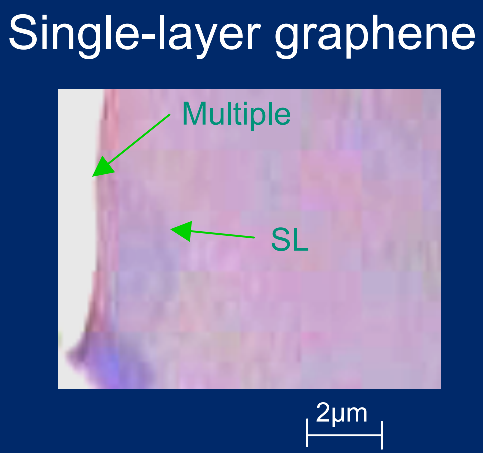


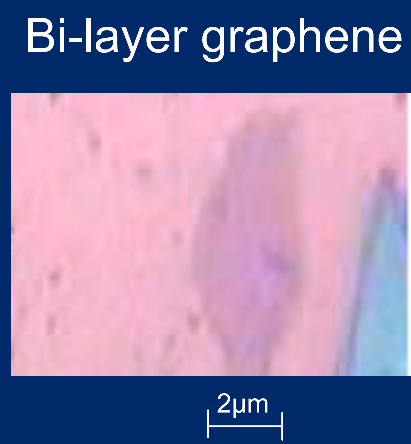
K. S. Novoselov *et al*, Science 2004; K. S. Novoselov *et al*, Nature 2005; Y. Zhang *et al*, Nature 2005.

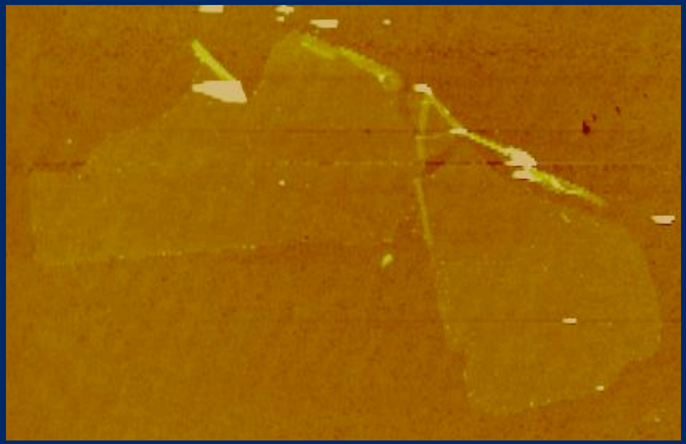
- Graphene was isolated for the first time in 2004
- Observation of QHE $\sigma_{xy}=4(n+1/2)e^2/h$
- Linear energy-momentum relation of electrons- massless, relativistic Dirac fermions ($v_F \approx c/300$)

Our goal: to study graphene coupled to superconductors

Device Fabrication

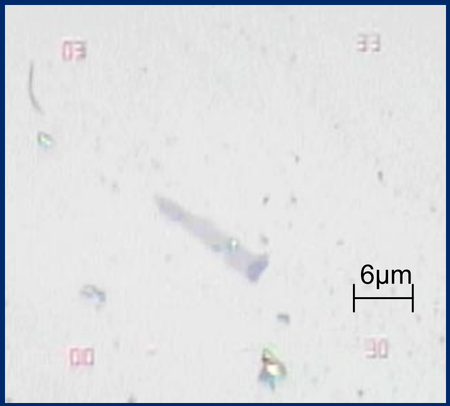




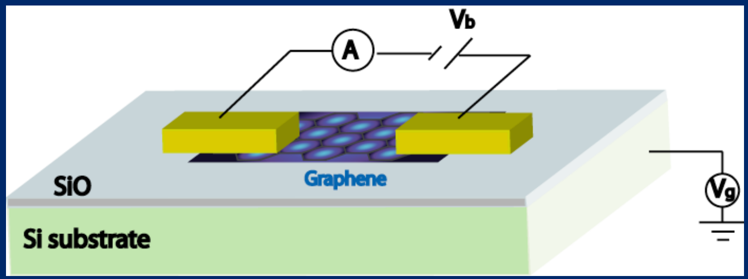


- Mechanical exfoliation -- rub natural graphite flakes onto SiO_2 substrate
- Identify the number of layers by color interference in optical microscope
- AFM images reveal mesoscopic features

Device Fabrication

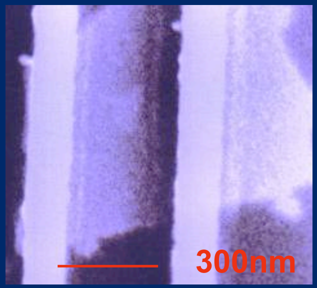


Two steps of E-beam lithography
- Alignment Marks
- Electrodes (10 nm Pd + 70 nm Al)

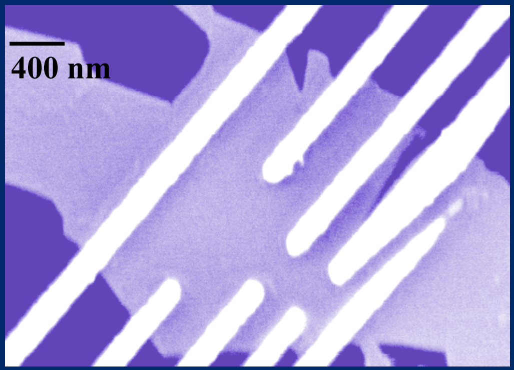


Bi-layer graphene device

Single-layer graphene device



2-Terminal geometry

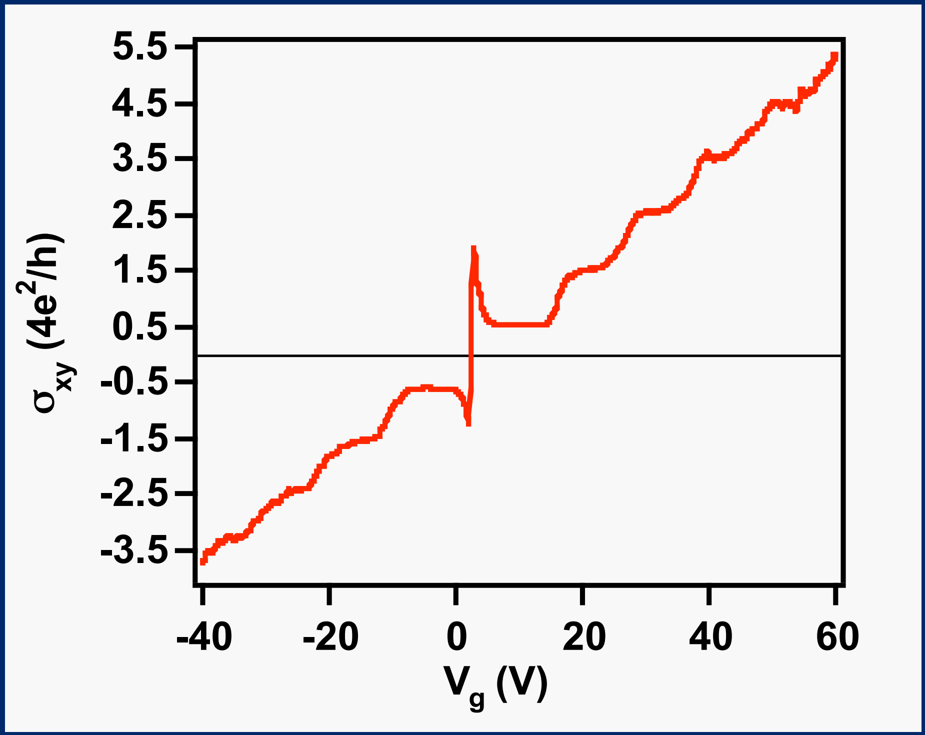


Hall bar geometry

Anomalous Quantum Hall Effect

Conductivity of single layer graphene quantized at half-integral values of $4e^2/h$

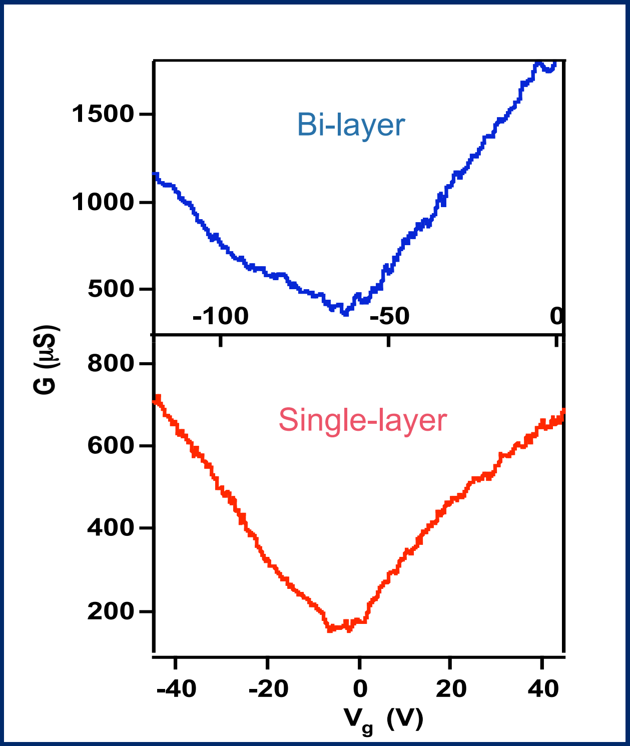
–> confirmed selection of single layer graphene

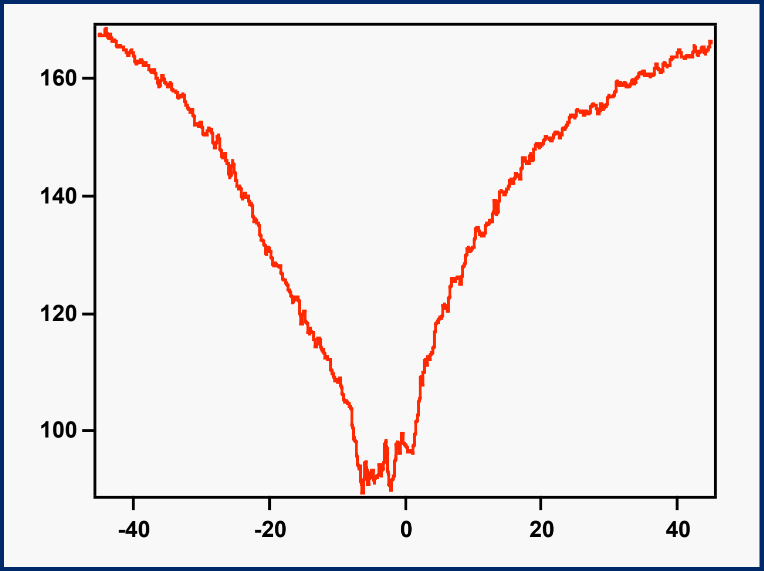


Measurement taken at B=8T and T=260mK

Bipolar Field Effect Transistor

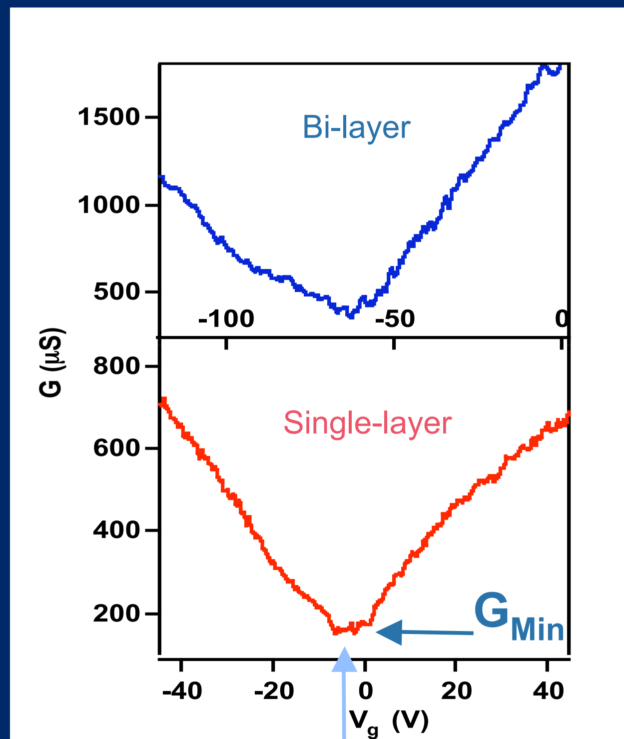
T=1.5 K



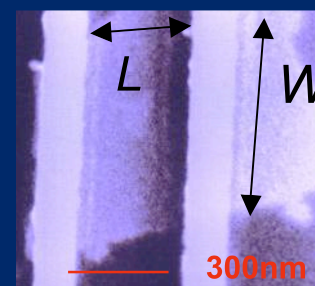


- Bipolar field effect observed in both single and bi-layer graphene devices
- G-V_g frequently displays sub-linear relationship

Bipolar Field Effect Transistor



Charge neutrality point



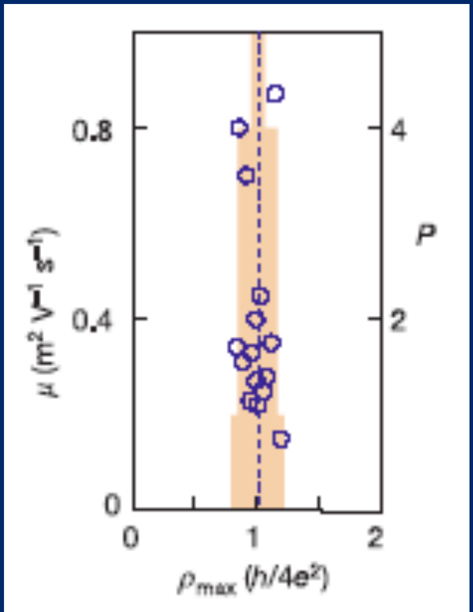
- At charge neutrality point → G_{min}
  minimum conductivity $\sigma_{min}=L/W\ G_{min}$

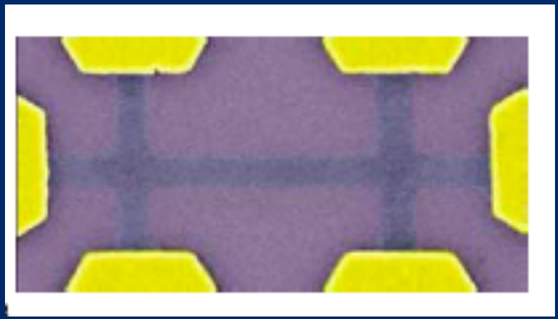
Minimum Conductivity – the mystery of missing π

- Theoretical prediction: universal value of $G_Q = 4e^2/\pi h$, independent of v_F.

  Fradkin 1986; Lee 1983; Peres *et al* (2006), Nilsson *et al* (2006), Katsnelson (2006), Tworzydlo *et al* (2006)…..
- Experimental measurements: $4e^2/h$

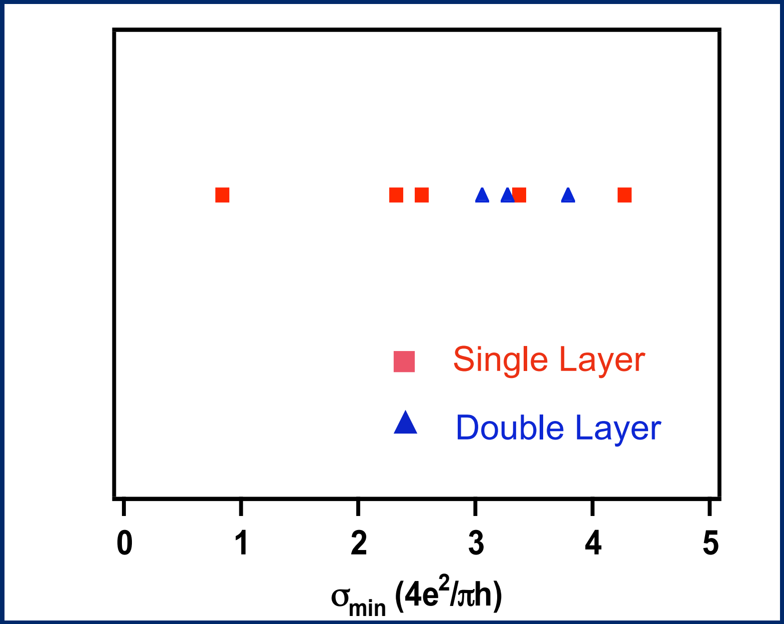
  (Novoselov *et al*, *Nature*, 2005.)

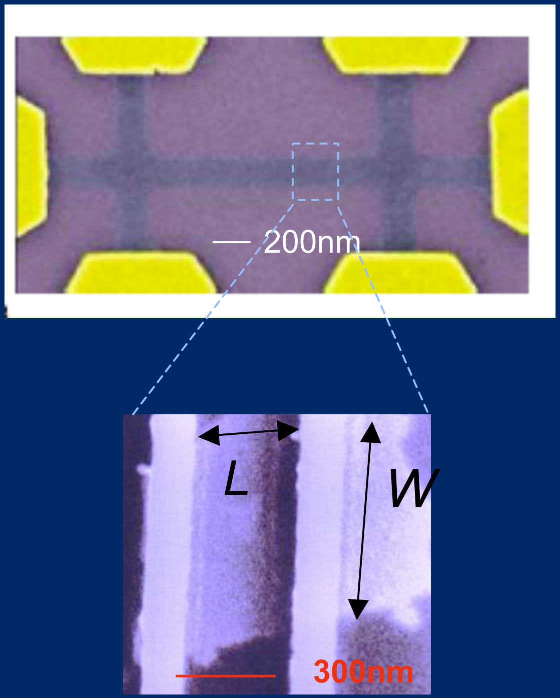




Minimum Conductivity – our data

- Our measured values of σ_{min} range from 0.8 to 4.3 G_Q.





Difference from previous experiments:
•Smaller inter-electrode spacing (100 - 400 nm)
•Larger aspect ratio *W/L*

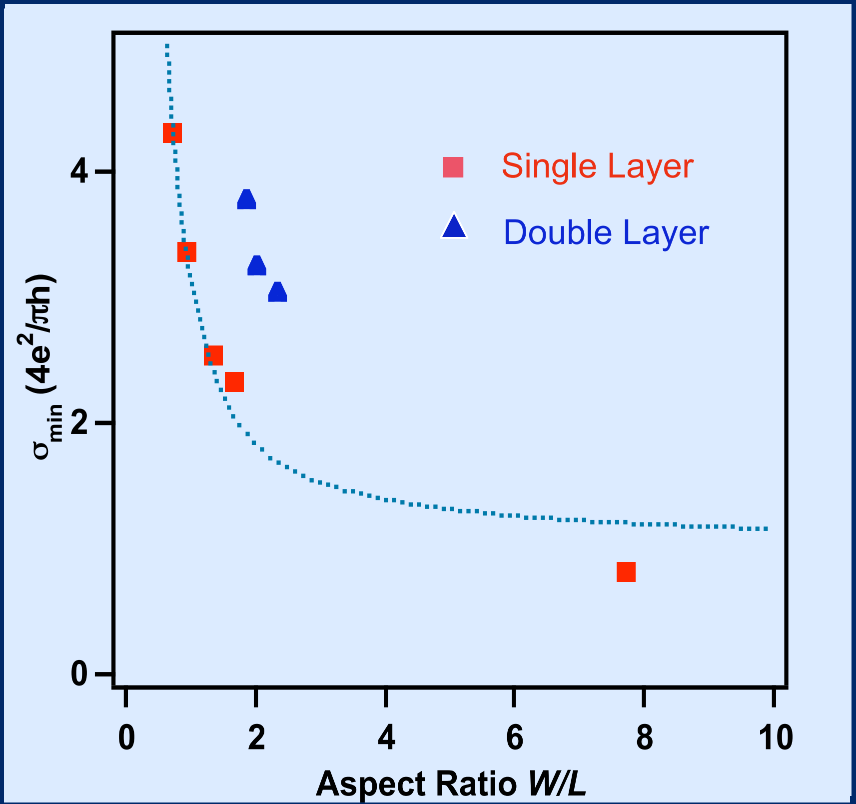
Minimum Conductivity
– shedding light on the mystery of missing π

Tworzydlo *et al*, *PRL*, 2006:

- σ_{min} depends on devices' aspect ratio *W/L* for a ballistic piece of graphene

$$T_n = \frac{1}{\cosh^2(\pi n L / W)}$$

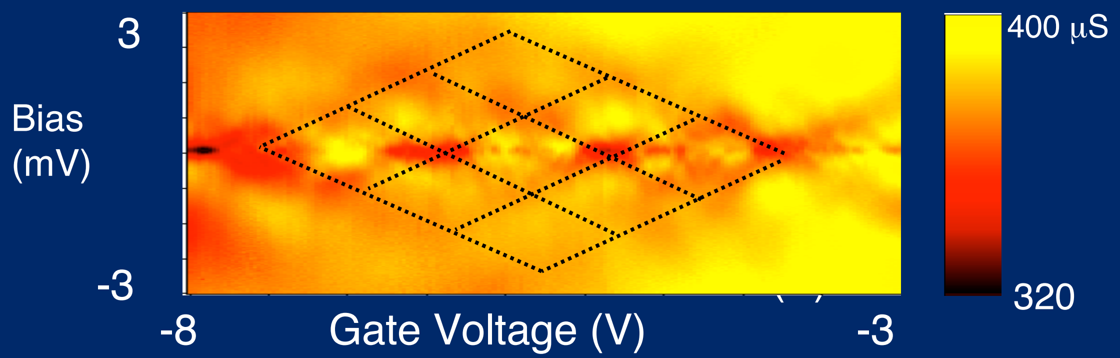
$$\sigma_{min} = G_{min}\frac{L}{W} = \frac{4e^2}{h}\frac{L}{W}\sum_{n=0}^{N-1} T_n$$

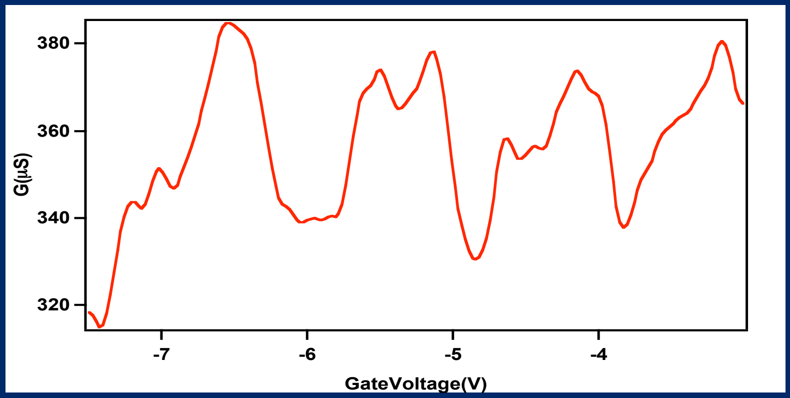


Good agreement with data with *no free parameters*.

Charge Transport in Graphene Devices

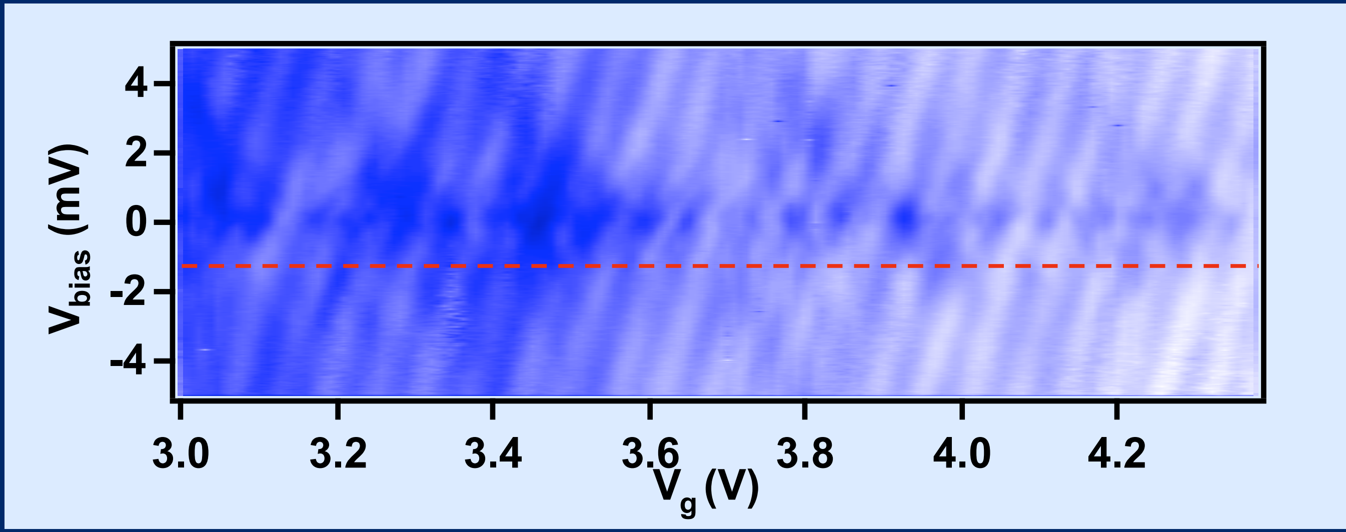
Graphene Coupled to Normal Electrodes at 260mK
(B= 40mT to suppress superconductivity in aluminum.)

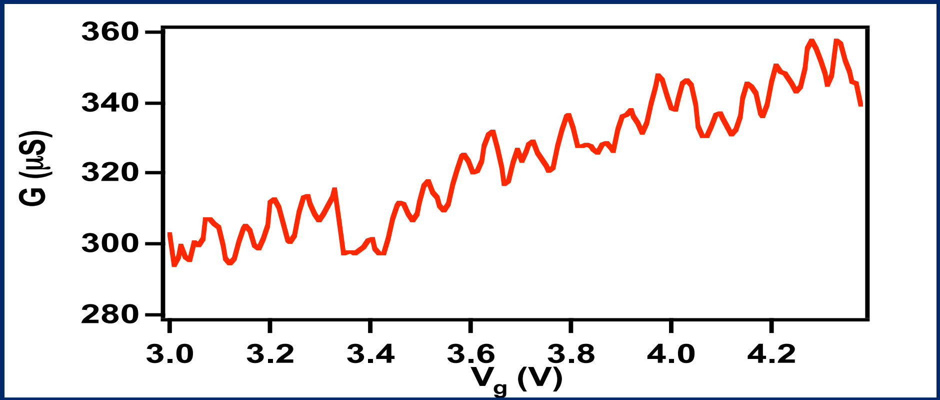




Periodic conductance oscillation as functions of both gate voltage and bias.

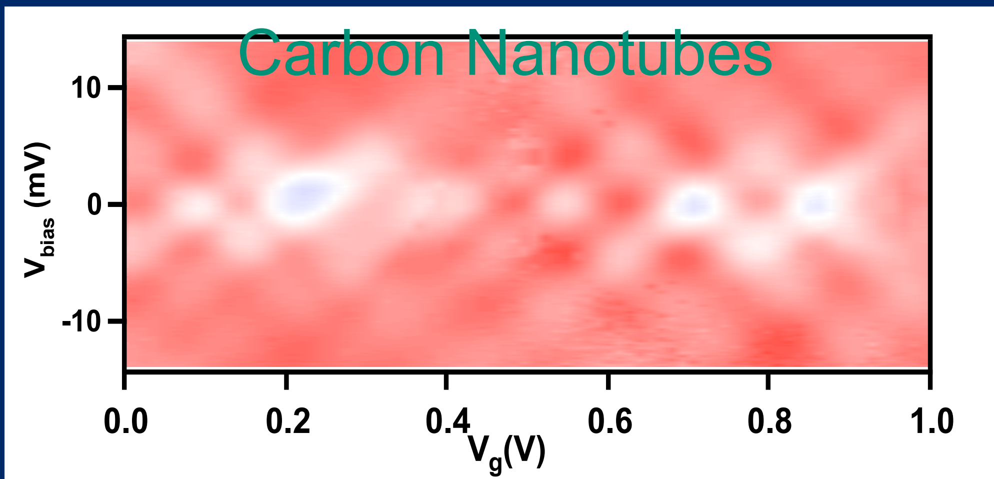
Charge Transport in Graphene Devices

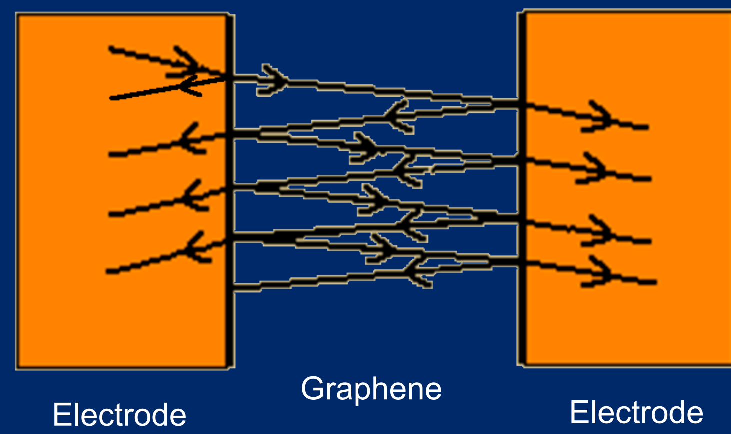




- Robust phenomena -- observed for both single and bi-layer devices, and for both hole- and electron-doped regimes.

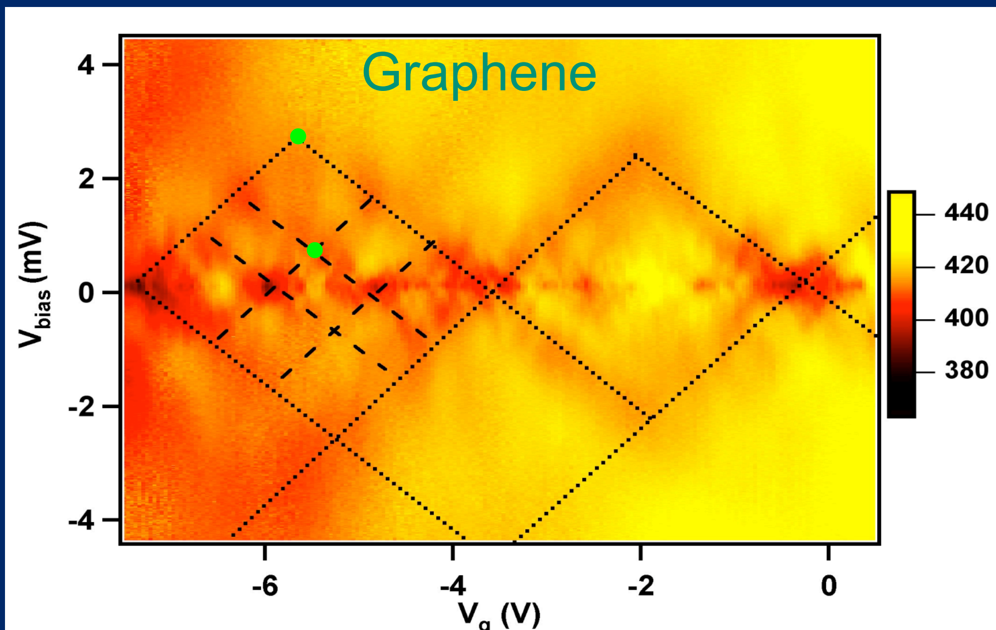
Quantum Interference of Electron Waves in Graphene

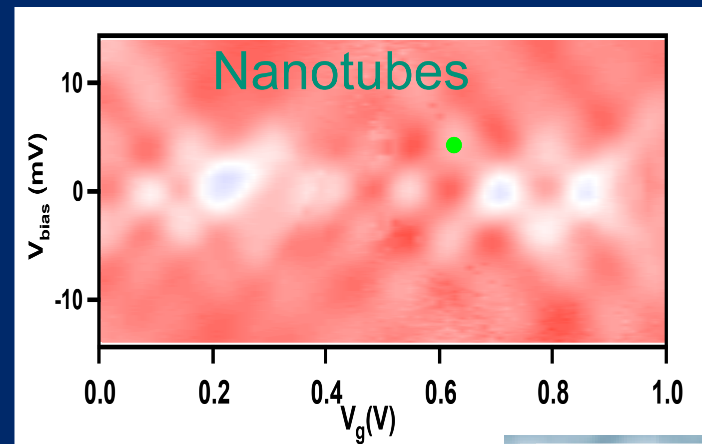


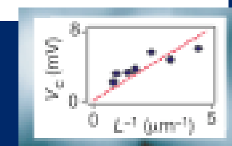


- Similar conductance oscillation observed in carbon nanotubes   Liang *et al*, Nature, 2001.
- Fabry-Perot resonant cavity -- interference of multiply-reflected electron and hole waves between partially transmitting electrodes.

Graphene as a Quantum Billiard





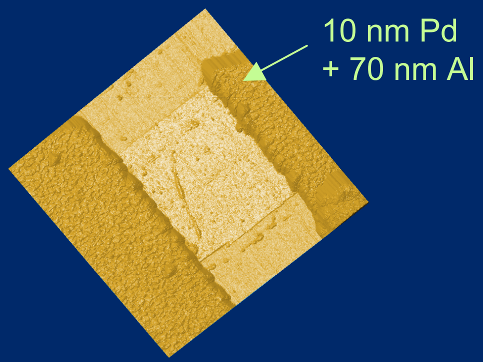


Liang *et al*, 2001.

- More than 1 period was observed in graphene devices
- Characteristic energy scale $E_o = hv_F/2L$
  - Nanotubes: L ~ inter-electrode spacing for nanotubes
  - Graphene: L ~ ?
- Electron paths in 2D graphene are not well-defined as in 1D nanotubes
- Smallest $E_o \sim 0.7$ meV → Charge coherence length > 5 μm in graphene

Graphene Coupled to Superconducting Electrodes

Josephson junction with massless Dirac fermions as the normal metal



Novel phenomena expected:

•Specular Andreev reflection
(Beenakker, *PRL* 2006, Titov and Beenakker, *PRB* 2006)

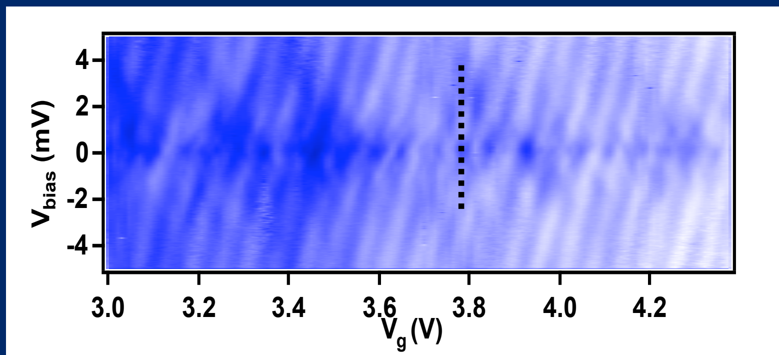
•Excitation gap of graphene channel and novel propagating modes of Andreev electrons (Titov, Ossipov and Beenakker, 2006)

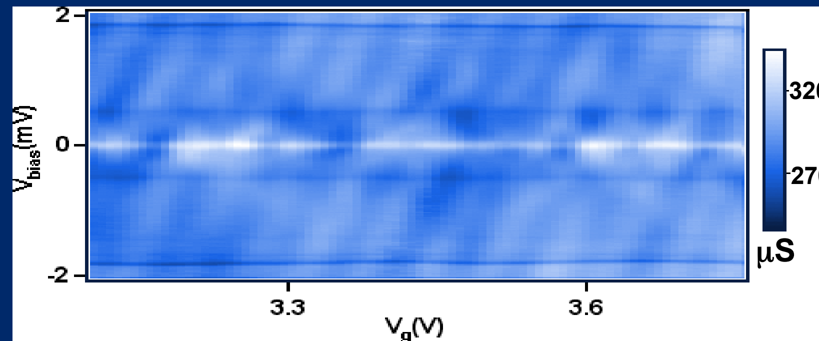
•Oscillation of tunneling probability with barrier width
(Sengupta 2006)

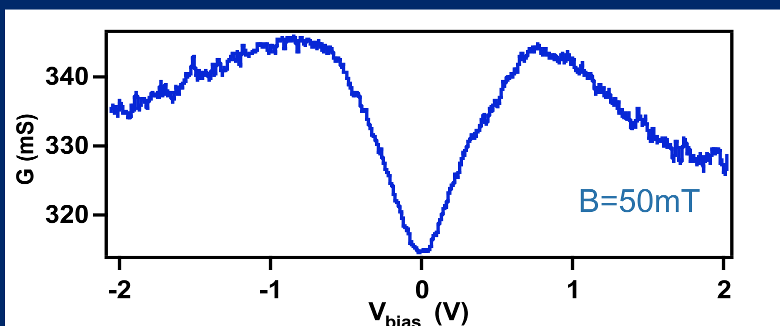
…

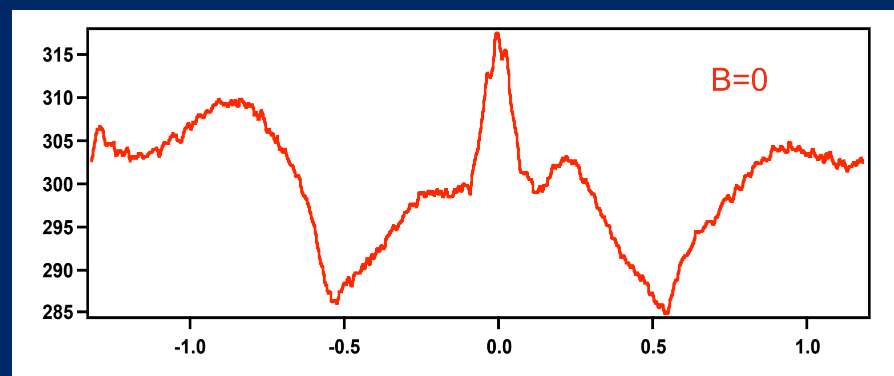
Superconducting Proximity Effect

Single-layer graphene T=260mK



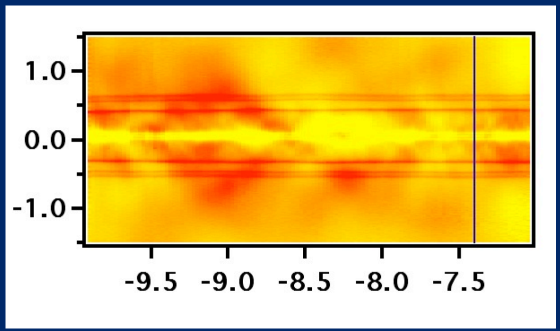


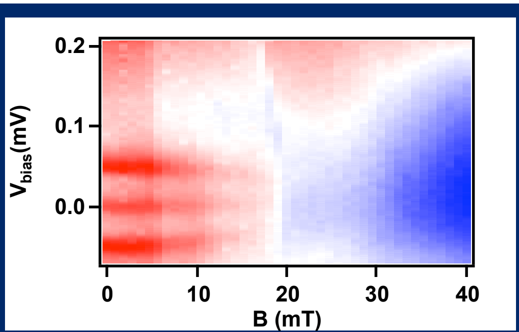


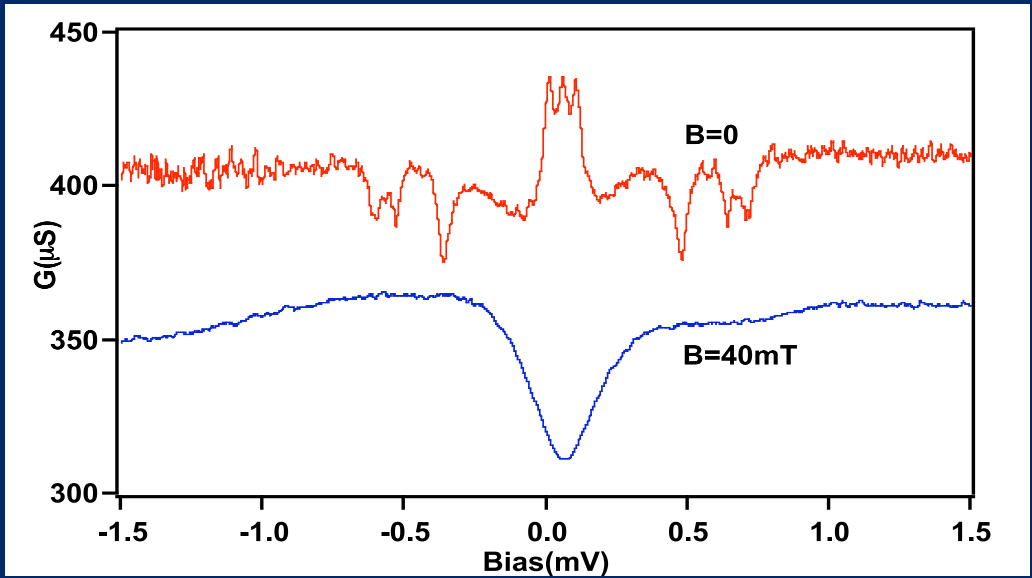


- Enhanced conductance at small V_{bias}<200µV – superconducting proximity effect.

Proximity Effect at Low-bias



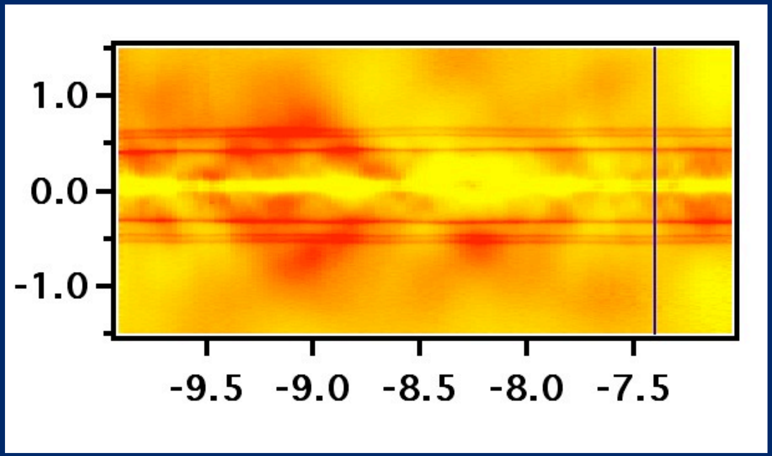


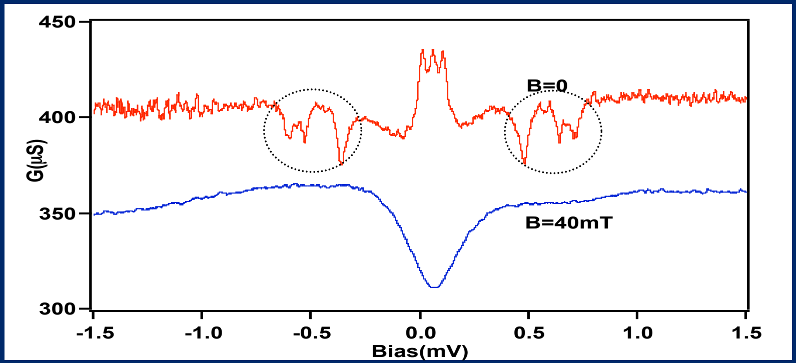


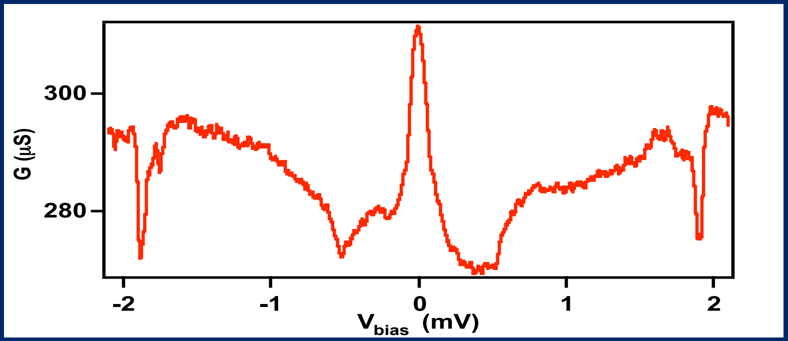
- the conductance display a single peak at zero bias
- two additional side peaks at ~ 50 μV(sub-gap structure)
- position of peaks suppressed by magnetic field

Similar low-bias peaks reported in superconductor-contacted few layer graphenes. (Shalos *et al*, cond-mat/0612058)

Anomalous Above-gap Conductance Dips



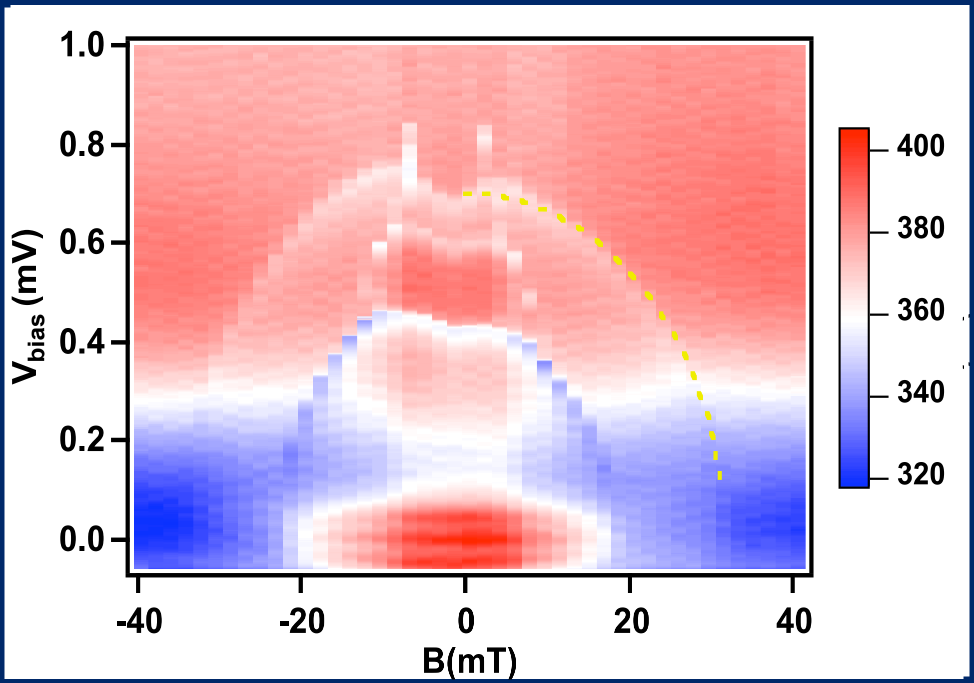




- Anomalous Conductance Dips at $V_{bias} >> \Delta$ (~200µV for Al)
- Independent of gate voltage
- Not observed for devices with resistance >20 kΩ

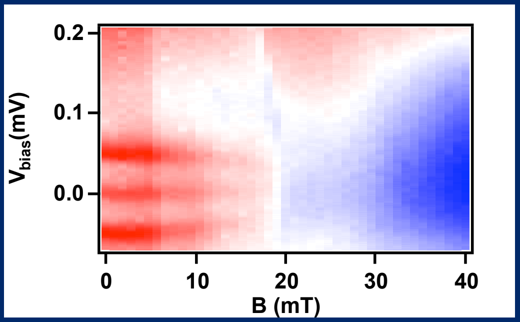
Dependence in Magnetic Field

Conductance as functions of bias and magnetic field



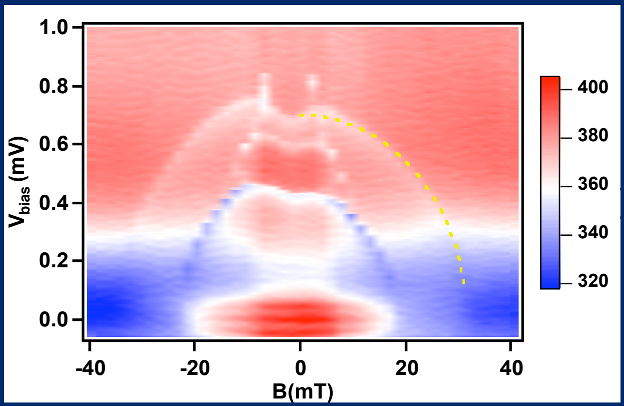
$$\Delta(H)=\Delta(0)\sqrt{1-\frac{H^2}{H_c^{\,2}(0)}}$$

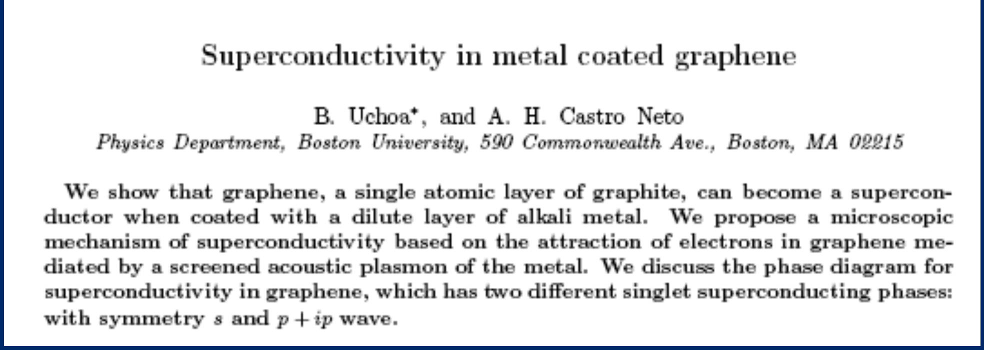
Douglass (1964).



- Zero-bias conductance peaks suppressed at 19mT.
- Above-gap Conductance dips suppressed at 32mT. *V(H)* curve resembles that of a superconducting gap, with $H_c \sim$ 32mT.

Signature of novel superconductors?





Superconductivity in metal coated graphene

B. Uchoa*, and A. H. Castro Neto
Physics Department, Boston University, 590 Commonwealth Ave., Boston, MA 02215

We show that graphene, a single atomic layer of graphite, can become a superconductor when coated with a dilute layer of alkali metal. We propose a microscopic mechanism of superconductivity based on the attraction of electrons in graphene mediated by a screened acoustic plasmon of the metal. We discuss the phase diagram for superconductivity in graphene, which has two different singlet superconducting phases: with symmetry s and $p + ip$ wave.

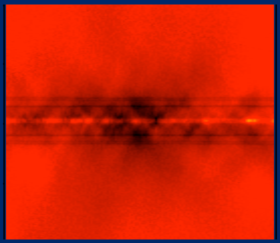
(2006)

- Plasmon-mediated superconductivity predicted in graphene coated with metal atoms.
- Possible signature of such superconductivity in graphene contacted with Pd
- Experiments underway for further investigation

Conclusion and Future Work

We investigated phase coherent transport of charges in single and bi-layer graphene devices.

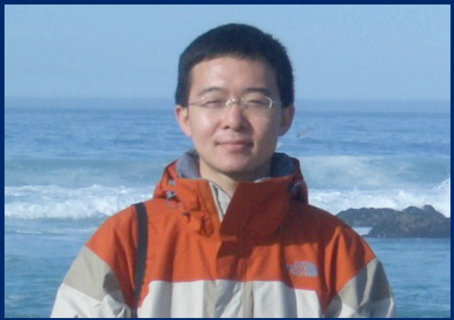
- ✓ Minimum conductivity of a wide strip of graphene approaches theoretical value of $4e^2/\pi h$.
  - ? Devices with different aspect ratios
  - ? Devices with different inter-electrode spacings
  - ? Conductivity in bi-layer graphene
- ✓ Graphene as quantum billiards -- Ballistic, phase coherent transport with coherence length >5 μm.
  - ? Chaotic trajectory, open billiards
  - ? Complicated patterns at Dirac point



- ✓ Proximity effect observed in graphene coupled to superconductors
  - ? Supercurrent (recently observed by Morpurgo group at Delft)
  - ? Specular Andreev reflection
  - ? Excitation gap
  - ? Plasmon-mediated superconductivity

Acknowledgement

Graduate Student



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